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Beyond the first optical depth: fusing optical data from ocean color imagery and gliders

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ABSTRACT

Optical properties derived from ocean color imagery represent vertically-integrated values from roughly the first attenuation length in the water column, thereby providing no information on the vertical structure. Robotic, in situ gliders, on the other hand, are not as synoptic, but provide the vertical structure. By linking measurements from these two platforms we can obtain a more complete environmental picture. We merged optical measurements derived from gliders with ocean color satellite imagery to reconstruct vertical structure of particle size spectra (PSD) in Antarctic shelf waters during January 2007. Satellite-derived PSD was estimated from reflectance ratios using the spectral slope of particulate backscattering ($\gamma_{b_{bp}}$). Average surface values (0-20 m depth) of $\gamma_{b_{bp}}$ were spatially coherent (1 to 50 km resolution) between space and in-water remote sensing estimates. This agreement was confirmed with shipboard vertical profiles of spectral backscattering (HydroScat-6). It is suggested the complimentary use of glider-satellite optical relationships, ancillary data (e.g., wind speed) and ecological interpretation of spatial changes on particle dynamics (e.g., phytoplankton growth) to model underwater light fields based on cloud-free ocean color imagery.

Keywords: Gliders, ocean color sensors, data fusion, remote sensing reflectance, particle size distribution, vertical structure, optical properties, Southern Ocean, marine waters

1. INTRODUCTION

Parameterization and prediction of 3-D underwater light fields in marine waters is a challenging task that involves the complimentary use of field measurements, satellite-based observations and three dimensional circulation models coupled to bio-geochemical processes[1]. Forecasting vertical structure of optical properties over large marine areas is usually achieved in two steps: 1) daily ingestion of data derived from spaceborne ocean color sensors into hybrid biological-hydrodynamic model, 2) correction of estimated values against true values using an assimilation scheme defined by a specific cost function[2].

Unlike satellites, glider-derived measurements allow full vertical characterization of optical fields even during cloudy conditions. Likewise, gliders can perform long-standing mapping without difficulty under extreme weather (e.g., hurricanes) becoming a safe and efficient alternative to shipboard surveys[3]. Despite these benefits, data streams provided by gliders are not synoptic and represent averaged 3-D scenes of underwater light climate during a specific interval of time. Therefore, the inclusion of glider-derived optical data into dynamic models of underwater light demands a fine understanding of spatio-temporal scales inherent to each group of glider-derived profiles. This is critical because two reasons: 1) glider-based data can fill 'gaps' of satellite surface observations by making 'synthetic' satellite-like imagery, and 2) time-space compatibility between glider and satellite optical retrievals may allow estimation of vertical distribution of optical properties from the space and over regions not covered by gliders.

In addition to the time-space mismatch, the interfacing and integration of satellite and glider optical measurements is also complicated by methodological differences in estimating the same optical properties. Satellite-derived retrievals of apparent (AOPs) and inherent (IOPs) optical properties in marine surface waters correspond to a vertically integrated

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picture of the first optical depth (i.e., $c\ z$, where c and z are the beam attenuation coefficient and water depth, respectively)[4]. In contrast, glider-attached optical sensors can produce detailed profiles of AOPs and IOPs with depth even beyond the photic zone. This makes gliders unique tools to discover important sub-surface features affecting sunlight penetration into the ocean such as thin layers[5]. Uncertainty of measuring optical properties also differ between above-water and submersible sensors as they are distinctly affected by atmospheric (e.g., aerosols) and in-water (e.g., biofouling) interferences.

In the present study, we compared optical measurements made from satellites and gliders platforms with the final intention of understanding relationships between above-water ocean color surface measurements and vertical distribution of some important optical properties determining light transmission trough the water column for a specific interval of time and space. We tested the idea that using additional satellite-derived ocean color products (e.g., chlorophyll a concentration, chl a, and particle size distribution, PSD) and wind-related characteristics we can obtain more information about shape of optical vertical profiles.
The experiment was conducted in Antarctic waters during the austral summer of 2006-2007 and put in evidence the importance of gliders to calibrate 3-D light models and minimize errors in estimating monthly satellite-derived composites of optical properties over areas with persistent cloudiness or sea ice cover.

2. METHODS

2.1 Geographic location of the experiment

As part of a long-term ecological research project (Palmer-LTER) funded by NSF-USA, the comparison between glider, shipboard and satellite optical data was performed in coastal waters west of Antarctic Peninsula (WAP) during the last three weeks of January of 2007 (Fig. 1). In general, bathymetry over the WAP is irregular and characterized by the presence of deep submarine canyons (>2000 m depth) cutting transversally the shallower shelf (~500 m).

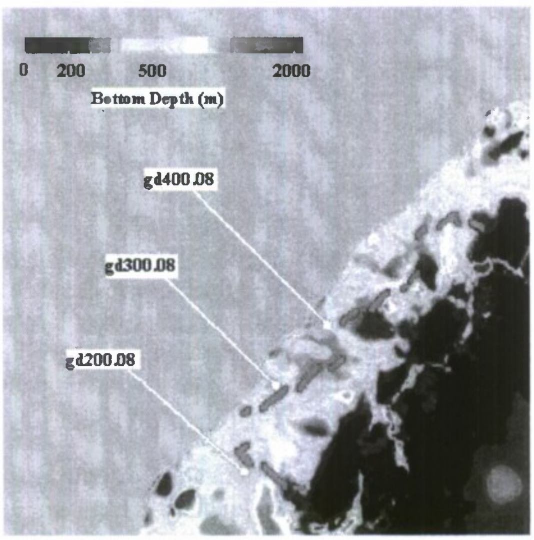

Fig 1. Bathymetric map of the study area and location of optical field measurements made during January of 2007. Antarctic Peninsula and archipelagos (black), waters deeper than 2000 m (grey), validation sites for optical measurements (white), and north to south glider track (magenta) are depicted with different colors. Glider and PRR optical profiles were compared in sampling locations 200.08 (67.3° S 71° W), 300.08 (66.5° S 70° W) and 400.08 (66° S 68° W). Cross-validation with HydroScat-6 casts was only performed in gd200.08 during January 25 (18:30 pm, local time).

Preliminary results showed that these topographic variations did not have a major influence on magnitude or vertical shape of optical properties during the period of study. Glider-based surveys started on January 8th from the northern part of the study area (64° S 64° W). Initially, the glider was allowed to flight perpendicular to the shelf (grid line 600) covering inshore and mid-shelf locations. At 80 km off the coast, the glider path was deflected to the south and

maintained until merging grid line 200 (67° S 72° W). Lastly, the glider trajectory continued southeast toward inshore waters near Adelaide Island where it was retrieved by a team of Rothera Station (British Antarctic Survey) (Fig. 1). Overall, the glider spanned in average two weeks to finish an along-shelf distance of 500 km. Ship discrete surveys using vertical optical profilers were also made with north-to-south direction covering each across-shelf grid line (10 oceanographic locations) in about one week. Multi-daily scenes of ocean color imagery overlapping the spatial domain of *in situ* optical measurements were collected during January. Reliable satellite-derived remote sensing reflectance (R_{rs}) determinations were only obtained during the first three weeks of January, thus there were no comparisons of satellite and glider optical data in the southernmost field sampling locations (grid line 200, 67° S 72° W to 67.5° S 69.5° W).

2.2 Optical measurements and ancillary information

Comparison between satellite and glider optical observations during January 2007 was based on three types of variables: 1) those related to the integration of above and below water optics (e.g., the spectral slope of particulate backscattering, $\gamma_{b_{bp}}$), 2) additional in-water optical properties needed for modeling and interpretation of $\gamma_{b_{bp}}$ profiles (e.g., water density, ρ, chl *a*, vertically diffuse attenuation coefficient of downwelling light, K_d), and 3) independent optical parameters to validate satellite-glider optical relationships (e.g., ship-based multispectral backscattering profiles). In addition, existing oceanographic data collected during the Palmer-LTER 2007 cruise (wind speed, W_s, abundance of heterotrophic bacteria and mesozooplankton) were analyzed in order to classify different vertical distributions of particle dynamics based on glider-based $\gamma_{b_{bp}}$ and connected to satellite-based $\gamma_{b_{bp}}$ estimates.

2.3 Glider surveys

Underwater autonomous measurements were performed with a Webb Slocum Coastal Electric glider equipped with a Sea-Bird CTD instrument, a chlorophyll-a fluorometer (excitation wavelength = 443 nm, WetLabs), and a three wavelength (470, 532, 660 nm) optical backscatter sensor (ECO-triplet poke, WetLabs). Unlike other glider types (e.g., spray, seaglider), the use of Slocums was especially advantageous in the WAP region to characterize fine vertical (~40 cm) and horizontal (~200 m) structure of optical properties due to their greater dive angle with respect to the vertical (25°)[6]. Also, Slocums offer an efficient satellite-communication and data transmission (i.e., antenna on the tail) even under typical windy conditions of the Southern Ocean.

In average, the Slocum glider had an average flight speed of 24 km per day and a maximum depth range of 100 m. Thus, moving forward at 0.25 m s^{-1}, an oblique section of the shelf is accomplished in approximately 1 hour. The number of profiles (down and up cast) in each 200 m horizontal segment varied according to the water column stratification (e.g., more dives in northern locations). Glider course was adjusted every surfacing by comparing glider-GPS readings with satellite-derived coordinates, and waypoints were decided based on CTD- derived geostrophic currents and current position. Glider navigation was controlled from the Cool Lab (Rutgers University) and using two-way Iridium cell phone telephony. Communication during glider testing before deployment and recovery was conducted with a Freewave high-bandwidth Local Area Network protocol.

For each geolocated data segment, raw science glider data streams (raw spectral backscattering and chl *a*, and CTD-derived GMT time, pressure, temperature and salinity) were first partitioned in upward and downward profiles and using different deflection detection algorithms (e.g., depth threshold, second derivative). Afterwards, spectral backscattering measurements were corrected due to pathtlength attenuation and based on satellite and PRR derived inherent optical properties[7]. Spectral slope ($\gamma_{b_{bp}}^{(glider)}$) of particulate backscattering coefficient (b_{bp}) was calculated with the following equation:

$$\log_{10}(b_b(\lambda) - b_w(\lambda)) = M + \gamma_{b_{bp}}^{(glider)} \log_{10}(\lambda_o/\lambda_i) \qquad (1)$$

where b_b and b_{bw} are total and water backscattering coefficient in m^{-1}, respectively, M is the magnitude of particulate backscattering at the reference wavelength λ_o and λ_i refers to the spectral channels of the optical instrument. Effect of ambient illumination on magnitude of chl *a* measurements was not assessed, thus only relative units are reported. The final processing step of glider observations consisted in data aggregation using the arithmetic average (horizontal bin = 1 km, vertical bin = 1 m) and linear interpolation of resulting values.

2.4 Analysis of satellite imagery and inversion of ocean color products

Merged local area coverage satellite scenes (MLAC) with 1.1 km resolution at nadir were obtained from SeaWiFS's (L2, http://oceancolour.gsfc.nasa.gov/, NASA). For each pixel and wavelength (λ = 443, 490), geolocated and atmospheric corrected normalized water leaving radiance (nL_W) was normalized by the extraterrestrial solar irradiance[8] to obtain $R_{rs}(\lambda)$. A posteriori, values of $\gamma_{b_{bp}}^{(sat)}$ were obtained using an empirical relationship[9] previously tested in the study area[7]:

$$\gamma_{b_{bp}}^{(sat)} = Y0 + Y1\, R_{rs}(443)/R_{rs}(488) \qquad Y0 = -1.13,\ Y1 = 2.57 \tag{2}$$

Notice that expression (2) assumes covariation between phytoplankton and colored dissolved organic matter absorption, and has a range (0.5 to 3) not necessarily equal in absolute terms to $\gamma_{b_{bp}}^{(glider)}$. In our study area, $\gamma_{b_{bp}}^{(sat)}$ values smaller than 1.668 are indicative of waters with a major contribution of large-sized (>20 μm) pigmented particulates[7]. To obtain a representative $\gamma_{b_{bp}}^{(sat)}$ per location, a monthly composite was calculated based on averaged values, and choosing only those pixels not contaminated by clouds, sea ice or sea surface reflection (NASA L2 quality flags).

2.5 Ship-based validation of glider and satellite optical estimations

Spectral backscattering measurements at one angle (140°) were made using a backscattering-meter profiler (HydroScat-6, Hobi Labs). In general, downcast samples were less influenced by instrument motion during descend, thus only downward profiles were compared with glider and satellite $\gamma_{b_{bp}}$ estimates. For each channel (442, 488, 532, 555, 620, 676 nm), uncorrected backscattering coefficient values (b_b') were computed from volume scattering function measurements at 140°[10]. Final total backscattering estimates were obtained by correcting b_b' with a scaling factor related to the optical system and inherent optical properties[10].

2.6 Ancillary datasets

Additional optical information along the vertical component was obtained with a profiling reflectance radiometer (PRR-810, Biospherical Instruments Inc.). Averaged spectral K_d at 1-m resolution was calculated as the regression slope between logarithm of downwelling irradiance and water depth[11]. Ecological interpretation of spatial changes on $\gamma_{b_{bp}}$ was carried out using concurrent environmental (wind speed 10-m above the sea surface) and biological (abundance of heterotrophic bacteria and Antarctic krill or *E. superba* per unit of seawater volume) data collected during January 2007 cruise (protocols at http://pal.lternet.edu/data/).

3. RESULTS AND DISCUSSION

3.1 Spatial agreement between satellite and glider estimations of particle size distribution

Spectral changes on particulate backscattering, as estimated from satellite and glider optical sensors, were spatially coherent in surface waters (up to 50 m depth) of 84% of the locations investigated in the WAP region (Fig. 2 and 3). This co-variability was clearly evidenced at spatial scales between 1 and 50 km (e.g., waters dominated by 'large particles' (mean diameter >20 μm) between 66°S 68.7° W and 65.3°S 68° W, Fig. 2 and 3), and was not greatly affected by day-night changes on glider-derived estimates.

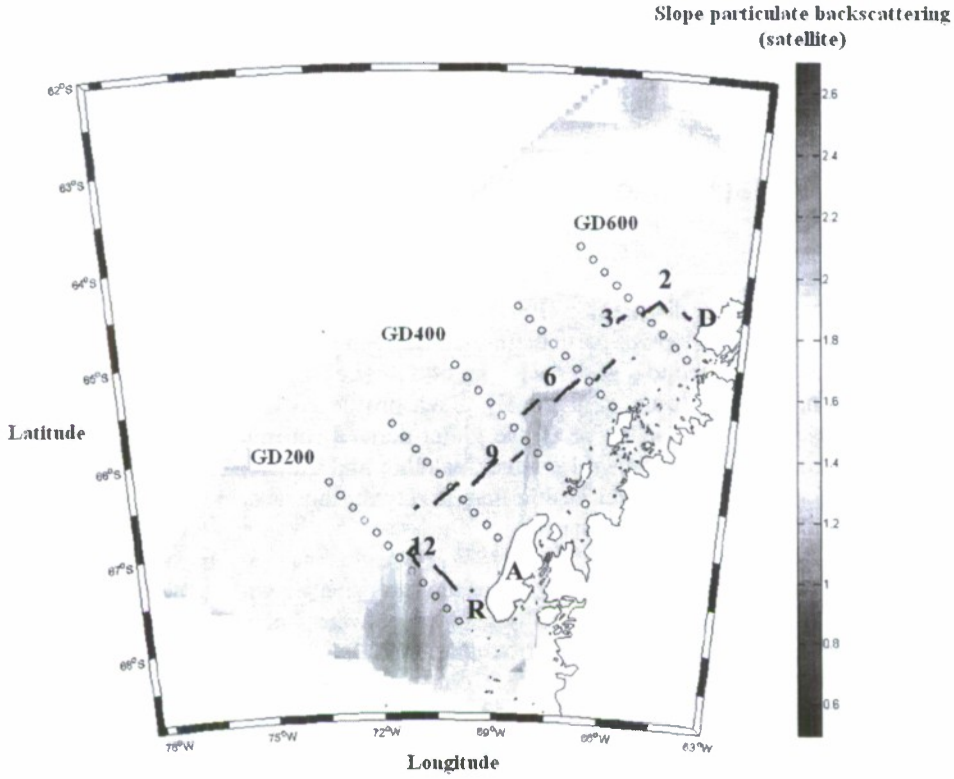

Fig. 2. Distribution of SeaWiFS-derived particle size distribution index over the WAP region. The map corresponds to Gouraud-interpolated monthly composite of multi-daily images during January of 2007. Particle size distribution index ($\gamma_{b_{bp}}^{(sat)}$) greater than 1.668 (i.e., pixels more reddish) represents waters dominated by 'small' particles (<20 μm). Glider track (broken black segments) and grid lines (GD) with all PRR stations (empty circles) occupied during the summer cruise are illustrated. D and R are glider deployment and retrieval sites, respectively, A is Adelaide Island. Numbers indicate different sets of glider data (segments) ordered in a chronological way (e.g., number 1 corresponds to the first group of profiles after deployment).

At the monthly scale, the major discrepancy between these two types of PSD estimates (bias >100%) was observed in the last two groups of glider profiles (i.e., segment # 13 and 14). This inconsistency was related to the lack of accurate SeaWiFS measurements during the last week of January, and caused by the presence of cloud-contaminated pixels in the southernmost sampling line (i.e., gd200, 68° S). Unlike satellite missing measurements, glider data gaps between segments did not alter the general 30-days agreement between spatial variability of SeaWiFS and slocum optical measurements.

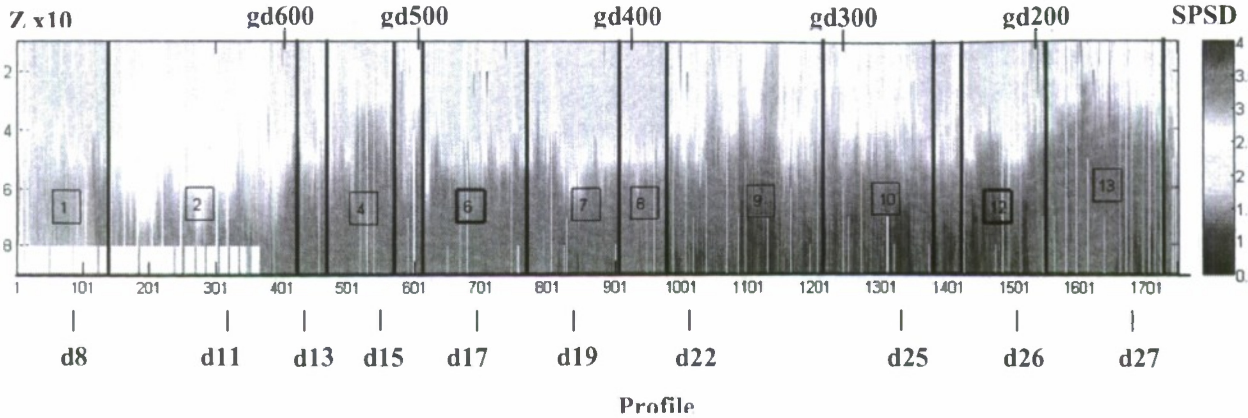

Fig. 3. A vertical cross-section of particle size distribution (PSD) estimates along the WAP shelf. For each glider profile (up or down cast, x-axis), PSD derived from slope of particulate backscattering (SPSD) is plotted as a function of depth (Z, y-axis) in m, numbers in squares correspond to a glider segment of data (i.e., a group of profiles) where 1 and 14 are the first and last data streams from north to south, respectively. Each profile contains data averaged every 1 m and interpolated using the Gouraud technique. Similar to Fig. 2, the glider-derived spectra particulate backscattering index also increases as particle size decreases and viceversa. However, satellite and glider PSD indexes are calculated in a different way resulting in relative comparisons. Lower scale refers to day during January 2007, upper scale represents along-shelf sampling lines (gd), white stripes mean no data.

In general, variation of optical properties retrieved from glider sensors was smaller with depth over SeaWiFS-detected patches dominated by relatively 'small' (<20 μm) particles (e.g., inshore waters of gd600, 64.5° S, 65.5° W versus versus 65.5° S, 67° W) (Fig. 2 and 3). This homogenous distribution of small-sized particles between 0 and 50 m depth commonly coincided with less variable PRR-derived K_d profiles. Contribution of optical components to light attenuation and as a function of depth was also unique in water parcels dominated by particulates with small dimensions (i.e., high spectral slope of b_{bp}). In fact for these locations, there was a drastic decrease (up to 40%) of heterotrophic bacteria toward the sea surface (e.g., gd300.08 and gd500.08) that suggests a greater role of phytoplankton and detritus with respect to bacteria modulating spectral shape of satellite and glider b_{bp} determinations within the first optical depth.

3.2 Segmentation of optical profiles according to surface ocean color features and wind speed

Vertical distribution of optical properties in our study area was constrained by biological (i.e., differential phytoplankton accumulation as a function of depth) and physical processes (e.g., exchange of particles between near-surface and deeper oceanic layers due to wind-driven mixing) (Fig. 4).

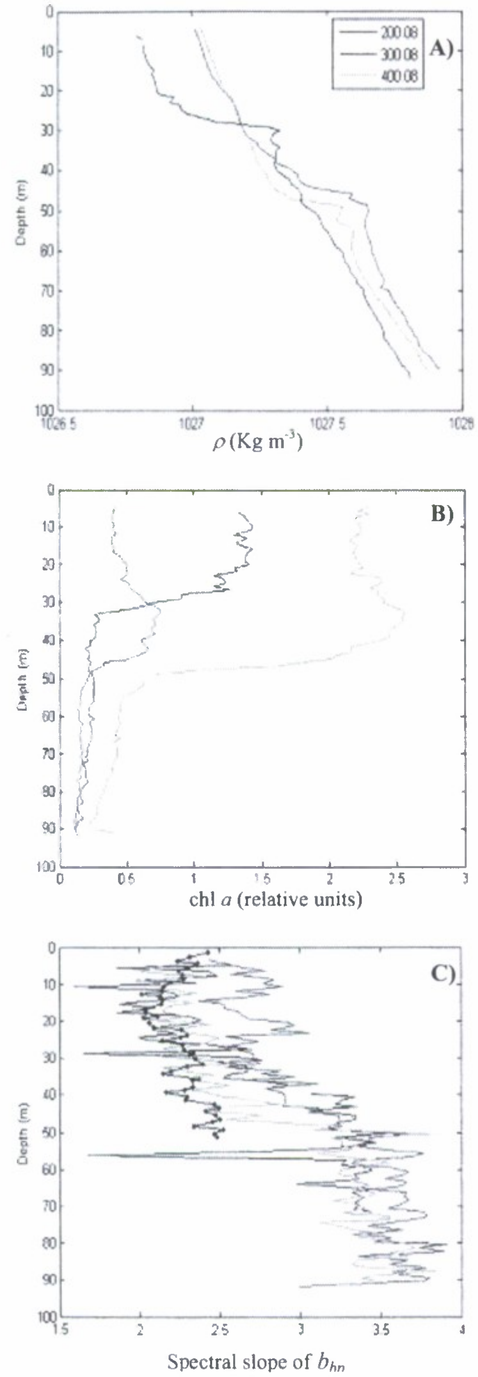

Fig. 4. Influence of mixed layer depth and wind speed on vertical distribution of phytoplankton and particle size distributions in three glider-sampling sites. Measurements were obtained by glider sensors between 1 and 88 m depth and averaged every meter. Profiles correspond to sampling sites 200.08 (68.28° S, 75.11° W, blue line), 300.08 (67.71° S, 73.28° W, red line) and 400.08 (67.11° S, 71.53° W, green line) (Fig. 1), A) CTD-derived seawater density (upcast), ρ, B) chlorophyll a concentration, chl a (upcast), and C) spectral slope of b_{bp}, $\gamma_{b_{bp}}$ (upcast), HydroScat-6 estimates in gd200.08 (downcast) are indicated with a black solid line and dots. Upper mixed layer depth and wind speed in gd200.08, gd300.08 and gd400.08 were 25, 20 and 30 m, and 3.5, 9.5 and 9 m s^{-1}, respectively.

In general, more stratified waters were found toward the southern part of the study area (gd200.08, 67° S, 71° W) in concert with a defined ($\Delta\rho/\Delta z$ = -0.4 g m^{-3} in 10 m depth) pycnocline (Fig. 4A), weak wind speeds (~2.5 m s^{-1}), a high proportion of 'large' particles ($\gamma_{b_{bp}}^{(glider)}$ < 2.5), and intermediate chl *a* values (up to 1.3 units). Likewise and unlike northern locations, fluorescence profiles in the southern mid-shelf evidenced an increase of chl *a* near the surface that coincided with relatively constant glider-derived PSD between 0 and 20 m depth (Fig. 4B and C). This vertical behavior of $\gamma_{b_{bp}}^{(glider)}$ was confirmed by independent measurements obtained with HydroScat-6 (Fig. 4C). Minimum differences on spectral slope of b_{bp} (<10% in average) were found when upcast glider profiles were validated with downcast HydroScat-6 data. In contrast, glider downcast profiles showed a substantial decrease of b_{bp} spectral slope above 10 m depth that was probably related to changes on sensor orientation and variation on bubbles concentration near the surface.

In the central part of the sampling grid (gd400.08, 66° S 68° W), the $\gamma_{b_{bp}}^{(glider)}$ also evidenced relatively 'large' particles (i.e., 'small' b_{bp} (λ) slopes) in the first optical depth (Fig. 4C). However, its vertical distribution presented a deeper maximum gradient associated to a deeper pycnocline (~45 m depth) and chlorophyll *a* peak (~45 m depth), and stronger winds (~8.5 m s^{-1}) (Fig. 4A-C). In contrast with the above locations, mid-shelf of grid line 300 (66.5° S, 70° W) was mainly represented by a homogenous layer (0-35 m depth) with relatively 'small' particles (i.e., 'large' $\gamma_{b_{bp}}^{(glider)}$) and low chl *a* values (< 1 units) Fig. 4B-C. The sub-surface chl *a* peak was situated at 32 m depth and slightly above the depth of drastic increase in glider-derived PSD (~40 m). Wind intensities were higher (~9 m s^{-1}) with respect to southern locations but density profiles suggested a less efficient mixing of the water column compared to northern locations due likely to an increase of water column stability caused by freshening of the upper layers (0-20 m depth) (Fig. 4A).

Preliminary analysis of ancillary data suggests the relative greater importance of phytoplankton growth with respect zooplankton grazing or bacterial decomposition of particulate material defining horizontal changes of glider and satellite PSD-indexes. Moreover, wind speed was a major responsible of optical geographic differences due mainly to surface accumulation of phytoplankton caused by changes on pycnocline and probably nutricline depths. In the vertical component, zooplankton and bacteria packaging of particulates was likely a major term affecting light profiles in mid-shelf waters of the WAP region during summer. Likewise, local variability on wind speed had an important role constraining shape of optical profiles due to changes on mixed layer depth and concomitant modifications on vertical position of chlorophyll *a* peaks and particle size ranges.

This work demonstrated the feasibility of combining glider and satellite optical streams to overcome difficulties associated with remote sensing mapping of IOPs over marine areas with persistent cloudiness or sea ice fields. Reconstruction of 3-D light fields, previously calibrated with shipboard and glider data, is proposed based on wind fields and multiple above-water ocean color products related to vertical distribution (e.g., PSD- index) and magnitude (e.g., chl *a* or particulate organic carbon) of optical water components.

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